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Control of a non-linear vacuum system through a PID controller

Sandra I. Pérez-Aguilar^{a,b,*}, Everardo E. Granda-Gutiérrez^b, Juan C. Díaz-Guillén^b,
Jorge Candelas-Ramírez^b^a*Centro de Tecnología Avanzada A.C., Av. del Retablo 150 Col Constituyentes Fovissste, Querétaro C.P. 76150, México.*^b*Corporación Mexicana de Investigación en Materiales S.A. de C.V., Ciencia y Tecnología 790 Saltillo 400, Saltillo C.P. 25290, México.*

Abstract

In this work obtaining and validating of a mathematical model of a plasma nitriding vacuum system is presented. The developed model is based on the analogy of a vacuum system with an electrical circuit. The model was performed with the aim to use it for the design and implementation of a Proportional Integral Derivative control algorithm. It has been demonstrated that this algorithm, which is based on the simulation on MATLAB Simulink, is suitable to the pressure control in the nitriding vacuum chamber.

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1. Introduction

Plasma nitriding is a technique based on glow discharge electrical phenomena, which is commonly used to improve the surface properties of several components and metallic parts used mainly in equipment and industrial machinery. Through this thermo-chemical treatment it is possible to increase the life time of these

* Corresponding author. Tel.: +52-844-411-3200; fax: +52-844-415-2151.

E-mail address: sandraperez@comimsa.com.

parts by increasing the surface hardness, the wear resistance and in some cases the corrosion resistance according with Dutrey et al. [1].

Plasma nitriding process is characterized to be a clean technology because the use of a N_2 / H_2 glow discharge at vacuum pressure. David Pye [2] mentions that additional to this advantage, this process promotes the minimum volumetric distortion of the pieces as well as the high control of the processing parameters to obtain specific characteristics on the surface of the pieces.

The process is carried out in a vacuum chamber with a controlled atmosphere of Nitrogen (N_2) and Hydrogen (H_2) in a range of 1.33×10^2 y 1.33×10^3 Pa. The work piece is heated about $500^\circ C$ and it is maintained constant during the process. Pessin et al. [3] indicate that in these conditions a plasma discharge is performed by the application of a pulsed voltage of direct current about 800 V of amplitude between the chamber (anode) and the work piece (cathode).

Chirino Ortega et al. [4] mention that the stability of the vacuum pressure in the processing chamber is critical because the plasma discharge characteristics depends on it and Shoaib, et al. [5] relate this pressure with the mechanical properties obtained on the work piece.

This is why it is necessary to add a pressure control system in the chamber to regulate the pressure for different conditions of gas flow of entrance. To implement a control algorithm for the system is required to have an approximation of the model of it and after that, proceed to design the controller based on the validated model; the modeling of a system to design a closed loop control is essential in the theory of control.

There are mainly three ways to obtain a model: a) by physical laws, b) by parameter identification methods and sometimes c) by both techniques: Passino-Yurkovich [6]. To use physical laws is necessary to know the system, its components and the mathematical relationships between them, nevertheless sometimes is difficult to obtain the model when disturbances exists, belonging to the process or not. By the other hand, in agreement with Rodríguez-López [7] the parameter identification requires to obtain experimental input and output data to apply one of the existing methods such as least square and its variants, stochastic approximation, instrumental variation, and so on.

In this work the model of the vacuum system of a plasma nitriding process and the design of a digital PID controller is presented. The equipment of the nitriding process was designed and currently it is under construction in the Corporación Mexicana de Investigación en Materiales, COMIMSA.

The model was obtained using a technique based on the comparison between an electrical network and the vacuum system components used by Pasquino et al. [8]. This method takes into account the similarity between the laws of voltages in an electric circuit and the pressures in a vacuum system, and it has the advantage of the existence of many programs of circuit analysis according with Ernst [9].

To finalize the control loop, a digital PID algorithm was implemented to the control elements: a butterfly valve moved by a step motor and a roots vacuum pump varying its speed. The main idea of this work is to demonstrate that with an appropriate and validated mathematical model of the system, it is possible to use it for the design of a simple controller.

2. Design

With the aim to obtain the system model, the basic principles of the electric circuit and the vacuum system have been analyzed.

2.1. Electrical circuit

The main components of an electrical passive circuit are the resistive, capacitive and inductive elements and a power supply. When the circuit is energized, an electrical current flows through the elements, in the

case of the resistive elements, its behavior is governed by the Ohm's law (equation (1)) and in the case of the capacitive ones by the equation (2).

$$V = R \cdot I \quad (1)$$

$$I = C \cdot \frac{dV}{dt} \quad (2)$$

Where V is voltage, I is the current, R the resistance value and C the capacitance.

In this work the performance of the inductances doesn't analyze because there isn't similar components in the vacuum system.

2.2. Vacuum system

In a vacuum system, the components are mainly a vacuum chamber and elements as valves, tubing, hose, ports and orifices. At the beginning of the process, there is a constant pressure in the chamber and a gas that flows through the system to the pump. The equation (3) shows the relation of the pressure P , with the gas flow Q and the conductance C .

$$P = Q \cdot \frac{1}{C} \quad (3)$$

As the same way, the ports, valves and connections are elements that put of resistance to the gas flow, as the resistance in an electric circuit. The conductance is proportional to the flow, this is, as the conductance decreases, the gas flow has more restriction to pass through an element.

2.3. Analogy

According to the foregoing, an analogy between such systems is established taking into account the relationships shown in the table 1.

Table 1. Relation between electrical metrics and vacuum metrics

Electrical Metrics	Vacuum metrics
Ohm's law	Gas flow
$I = G \cdot V$	$Q = C \cdot P$
Charge of capacitor of capacitance C	Change in gas content in a volume V
$I = C \cdot dV / dt$	$Q = V \cdot dP / dt$
I - Electrical current [A]	Q - Flow [Torr l/s]
G - Electrical conductance [$1/\Omega$]	C - Conductance of element [l/s]
V - Voltage drop [V]	P - Pressure [Torr]
C - Capacitance [F]	V - Volume [l]

In this way, as Yin et al. [10] affirm, an electric resistance is the inverse of the conductance in vacuum and the capacitance is proportional to an element volume. By the other hand, a resistance to ground is a vacuum pump, a current power supply is a gas source and a “T” RC array is similar to the performance of a vacuum chamber and its volume.

2.4. Vacuum concepts

In vacuum concepts, the conductance can be expressed as the quantity flow rate of gas molecules flowing through a device in a period of time. Harris [11] cites that it depends on the diameter and length of a tube and it is affected by factors as surface roughness, the amount of bending of the pipe, the holes, the pumping speed, the type and characteristics of the gas and the pressure.

According to the vacuum pressure ranges, there are three regions to describe the gas flow. The pressure region 1×10^5 to 1×10^2 Pa the flow is termed continuum, and it can be turbulent or laminar. In the pressure range below 1×10^{-1} Pa the flow is molecular and in the range 1×10^2 to 1×10^{-1} Pa between continuum and molecular the flow is termed transitional.

In the transitional and continuum regions there is a dependence of the conductance with the pressure by the collisions of the molecules one with another. On the molecular region the molecules move freely and collisions are mainly with the tube wall, then pumping occurs only when molecules migrate into the pump of their own accord.

The calculation of the conductance for the continuum flow is by equation (4), for transitional flow is by equation (5) and for the molecular flow by equation (6).

$$C_v = \frac{K \cdot D^4 \cdot P}{L} \quad (4)$$

$$C_t = \frac{D^3}{L} \left[K \cdot D \cdot P + 12.1 \cdot \left(\frac{1 + 192 \cdot D \cdot P}{1 + 237 \cdot D \cdot P} \right) \right] \quad (5)$$

$$C_m = \frac{K \cdot D^3}{L} \quad (6)$$

On the equations, K is the constant of pressure unit conversion, D the tube diameter, L the length and P is the average pressure in the pipe.

2.5. System description

The nitriding equipment vacuum system consists of a 2000 liters capacity chamber, which is gas filling by means of flow mass controllers. In the output there is a hose of 5 cm diameter and 1 m of length, a butterfly valve and a pumping unit composed by a rotary vane and a roots vacuum pump. The pressure is constant monitoring by means of a capacitive sensor. This system is represented in the figure 1(a).

Doing the conversions according to the analogy presented, the electrical circuit obtained is shown in figure 1(b). The circuit was simplified taking in account only the most representative elements, since the valve and the reducer nipple have small volumes and are considered negligible.

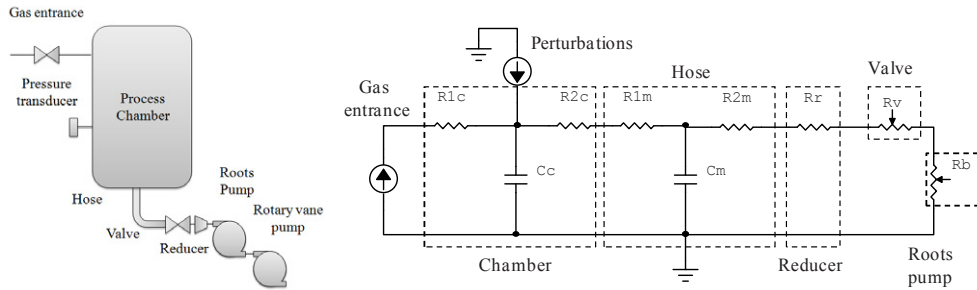


Fig. 1. (a) Diagram of the vacuum system; (b) vacuum system equivalent circuit

2.6. Simulation and model verification

The simplified circuit of the figure 1(b) was constructed in MATLAB Simulink taking into account the mathematical representations of the components. With this circuit a simulation was carried out with the aim of getting the step response of the system. Then starting from this data, through the Identification toolbox of MATLAB, an approximated mathematical model that represents its behavior can be obtained.

To develop the simulation was required to model the pumping speed of the roots vacuum pump based on the technical information of its datasheet (Alcatel [12]). The mathematical equation is shown on equation (7). Additionally, the equation (5) was used to get the chamber and hose mathematical representation of the conductance in the transitional flow; this is because the pressure of the system is in this range.

$$S_b = 0.29x^7 + 1.24x^6 - 0.35x^5 - 4.6x^4 - 1.73x^3 - 35.09x^2 - 30.72x + 243.61 + \frac{f-50}{10} \cdot p_1 \quad (7)$$

$$p_1 = 0.18x^8 + 0.8x^7 - 0.39x^6 - 4.55x^5 - 0.19x^4 + 3.89x^3 - 20.86x^2 + 8.57x + 73.16$$

According to this, the block diagram for the simulation is as shown in the figure 2(a). The output of such simulation is the chamber pressure with a constant inlet gas flow, and the conductance of the hose and chamber, as a function of the pressure. Additionally the conductance of the orifice between the chamber and the hose, and the conductance of the 90 degree vent valve for the pump, have been taken into account in the diagram and are shown as R_o and R_{vv} .

The conditions used for the simulation were: an initial voltage on the capacitors of 75 V (equivalent to 1×10^4 Pa), a step signal of 8.5 A (equivalent to 1.131×10^3 Pa l/s), 60 Hz of frequency for the speed of the roots vacuum motor pump and a sampling period of 0.01 seconds.

The simulation starts with a minimal current of 1 A of inlet, letting the voltage to drop due to the nature of the system. When the voltage stabilizes at a minimum value, a current step signal is applied. The data of the response to this step was entered into the identification toolbox of MATLAB, to approximate them to a mathematical model. The model obtained corresponds to an autoregressive model with external input presented as ARX [9 5 1]. This model was selected due to its approximation of 99 % instead of other models of lower order like the ARX [3 3 1] with lower percentage of approximation. Aguado [13] reports that the ARX model characterizes by being a linear discrete model determined by means of linear multivariable regression to minimize the squared difference between the real values and the calculated ones by the model.

According to the ARX [na nb nk] nomenclature, na is the number of poles, nb is the number of zeroes plus one, and nk is the number of samples of dead time. This model obtained by the simulation in z representation, is on equation (8).

$$\frac{I(z)}{V(z)} = \frac{9.245e^{-6}z^8 + 1.344e^{-6}z^7 - 1.729e^{-6}z^6 - 1.256e^{-5}z^5 + 3.7e^{-6}z^4}{z^9 + 5.3e^{-4}z^8 - 8.07e^{-2}z^7 - 2.3z^6 + 7.5e^{-2}z^5 + 2.24e^{-2}z^4 + 1.7z^3 - 7.5e^{-2}z^2 + 5.8e^{-2}z - 3.6e^{-1}} \quad (8)$$

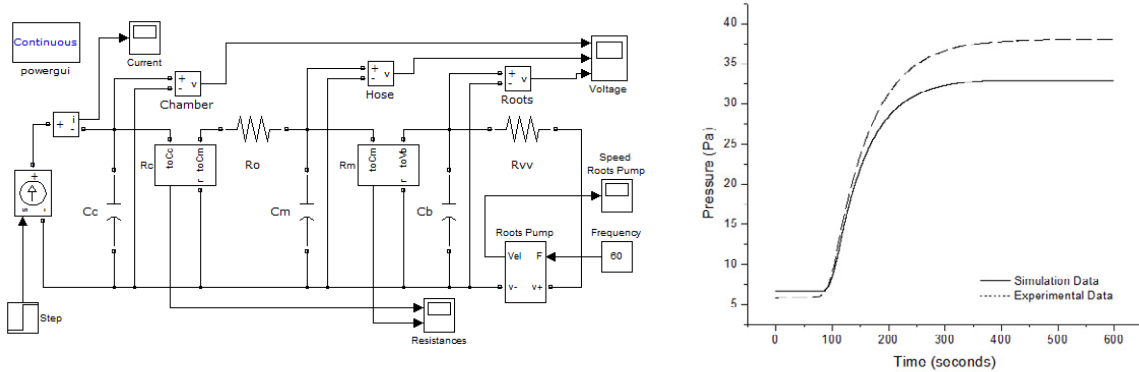


Fig. 2. a) Block diagram for the simulation on Simulink b) Pressure of the simulated and validated data.

In order to verify that the obtained model is suitable for the use in the design of the PID controller, the experimental data obtained from the nitriding equipment were submitted to the same procedure used in the simulation.

A flow step signal of 1.131×10^3 Pa l/s was applied once the pressure was established to a minimum. The pressure data obtained were entered into the Identification toolbox of MATLAB. Similar to the simulation, the experimental response fits to an ARX [9 5 1] model with a 98 % of approximation. The approximation of the ARX [3 3 1] model, also obtained with the experimental data, was 97 %.

Its z representation is shown on equation (9). The simulation and validation data are shown in the figure 2(b). Here can be appreciated an 85% of approximation between the simulation and experimental data. According to the experimental information, this degree of accuracy is 96 % for a pressure of 1.33×10^2 Pa and 99.5 % for a pressure of 1.63×10^2 Pa, this pressure values are in the range in which the equipment will be operated. In agreement to this, is validated the use of the mathematical model derived from the simulation for the controller design.

$$\frac{I(z)}{V(z)} = \frac{0.001084z^8 - 0.001702z^7 + 0.001134z^6 - 0.002033z^5 + 0.001626z^4}{z^9 - 0.968z^8 - 0.114z^7 + 0.0273z^6 - 0.0323z^5 + 0.0117z^4 + 0.0139z^3 - 0.00619z^2 - 0.0542z + 0.125} \quad (9)$$

3. Results

From these results and from the experience with the system, it can be noted that the system has a slow response and it is free of oscillations, therefore, is possible the implementation of a PID algorithm. The ability of these controllers to meet most of the control objectives has led to their widespread acceptance in the control industry (Ali [14]). This algorithm is not only well known by the most of the engineers but also has the

The following are the simulation conditions: a flux inlet of 1.066×10^4 Pa l/s, a set point of 266 Pa (2 Torr), frequency range of 40 to 60 Hz, valve aperture angle of 30 to 90° and an impulse disturbance of 1.33×10^3 Pa l/s for 30 seconds after the pressure stabilization.

The result was an amplitude in the pressure of 274 Pa (2.04 Torr) a 2 % of the set point, and an establishment time of 3 minutes which is adequate for this system. The signals of the control elements (valve and roots vacuum pump) are displayed in the figure 4(a) and in the figure 4(b) can be appreciated the chamber pressure and the detail in the moment of the perturbation.

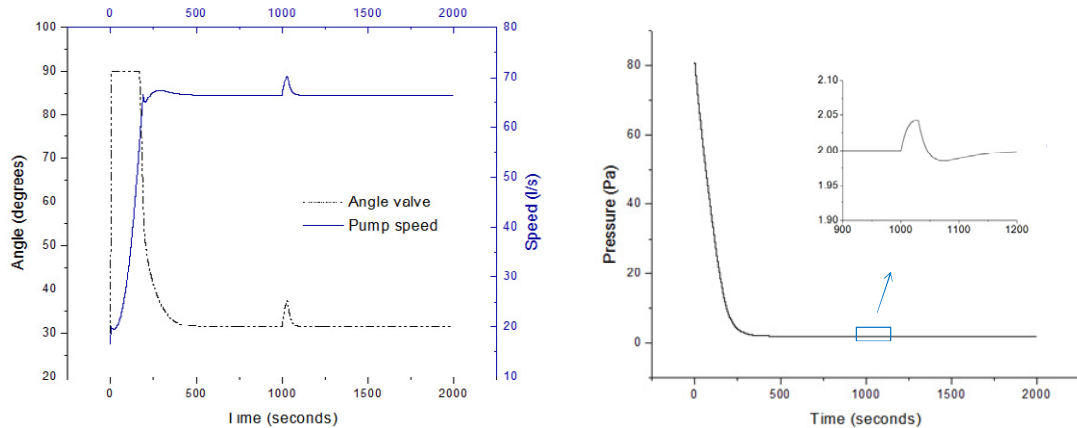


Fig. 4 a) Signals of the control devices b) System Pressure and detail of perturbation.

4. Conclusions

A mathematical model of a vacuum system was obtained through the analogy with an electrical system. This model was included in a simulation to implement a PID controller.

Both, the vacuum system model and the controller have been validated with real data, and according to the experience with the nitriding process, the obtained values are consistent in magnitude and time.

The design of a digital PID controller is used to regulate the pressure in the chamber of a nitriding system. In accordance with the simulation, in which were included the models of the roots vacuum pump and the butterfly valve as control elements, the controller is capable of maintaining the pressure in the 2 % of variation with a perturbation of 1.33×10^3 Pa l/s.

In a future work the author pretend to test out these results by the implementation of the algorithm proposed here in a digital microcontroller.

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